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LITERATURE SEARCH AND COMPREHENSIVE BIBLIOGRAPHY OF WINGS IN GROUND EFFECT AND RELATED PHENOMENA

by

William F. Foshag

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SUMMARY

A comprehensive survey and literature search is made of the general field of wings operating in ground effect and related phenomena. Comments are included of some of the papers published, to present a sketch of the methods of approach of a number of authors. The bibliography presents sources which consider the problem from the theoretical, experimental, and/or applications point of view. Tables are included which provide a convenient breakdown of the various sources, for a quicker method of locating specific references dealing with an area of special interest to the reader.

INTRODUCTION

The application of the ground effect phenomenon to over-surface high-speed transportation has created a new technology. A winged system flying in close proximity to the surface is considered one of the group or family commonly called ground effect machines (GEM's) or air cushion vehicles. It may be considered that this new technology is at about the same level of inquiry as the early aircraft industry was in 1910. Further, it may be considered that the application of the wing-in-ground-effect (hereafter called WIG) principle at the time of this writing (1965) has been reduced to a practical craft in only a few instances. Therefore, it was felt that all sources should be included in a literature review which might provide an understanding of this phenomenon and/or its applications. The selection of sources was made primarily on the basis of direct interest to the aerodynamicist and practicing engineer. Nevertheless, the inclusion of entries such as popular articles, patent descriptions, early reports, and unusual comments is intended for general background and as assistance to patent attorneys, aeronautical historians, naval architects, and other interested individuals. Generally, it may be said that it is the intent of this bibliography to suggest or support initial inquiry or investigation into the phenomenon of wings in ground effect.

The bibliography therefore includes a comprehensive collection of material which covers the theoretical and experimental aspects of the WIG. The search was extended to include references which show application

of the phenomenon to practice. This extension gives a liberal interpretation of the WIG phenomena, in an attempt to suggest possible extension of past engineering concepts to potential future applications.

A comprehensive understanding of the WIG would not be complete without an accounting for the practice of nature in this area. One cannot avoid realizing that the flying fish and certain seabirds take advantage of the surface effect of the ocean. Their performance may arouse our interest and perhaps indicate methods of near-surface flight maneuver and control.

SCOPE OF THE SURVEY

An outline of the scope of this bibliography is in order here. Generally, it may be considered that reference made to any form of sustaining fixed surface (airfoil or wing system) which receives or augments its lift by reason of its forward motion over a proximate surface will be included here. Also, it is considered that this wing lift may be further supplemented by the use of air-jet sealing curtains, which may be considered to operate continually or partially during the flight over the surface.

The bibliography therefore contains a comprehensive collection of references of the following air-jet systems only when they are in proximity to the ground and in forward motion: Jet Flap, GETOL, and Channel Flow Wing (side jet curtains).

A review of naval engineering literature reveals that the utilization of aerodynamic lift to displacement and planing craft is not unknown. Those sources and descriptions of naval craft and boats in which definite aerodynamic lifting shapes or surfaces are present to assist in the reduction of hull resistance are included in this report.

There are a few inclusions in this report of references on the resistance and/or stability of wheeled vehicles moving over a land surface. These few references are included because of their description of related problems, especially in wind-tunnel testing techniques over a ground board.

Also searched and included in this report is a full listing of sources covering the testing and application of sponsons or stub wings to flying boat hulls. The stub wing may well be considered an aerodynamic

lifting surface when clear of the water. An extension of this system, in which a wing may be aided in leaving the water surface by the use of the seaplane planing hull, will suggest further applications for practical ram wings.

A system related to the stub wing is included. This system has been called by NASA the "float wing" or integrated planing hull. This arrangement, which is well adaptable to ram wing vehicles, is one in which the flying boat planing hull is faired directly into the complete wing. The wing, which is somewhat awash when the craft is at rest, serves as the lateral stabilizer for the craft when at rest and when taking off. More generally, the hydrodynamic considerations of the WIG when taking off or landing on the water have yet to be fully explored.

A recent development (which utilizes sidewalls submerged in water) is the captured air bubble (CAB) type GEM. Although it is not sustained over the surface as a pure wing, it may, during high-speed cruise, be lifted by the ram pressure as it enters a forward-facing opening, or door. The border line between a WIG and a CAB can, at times, be thin. This report omits coverage of the CAB, since this development is still quite new and would best be included among works pertaining to GEM's which utilize systems of air-moving machinery for the prime source of lift.

A patent search was made to uncover references which would indicate the application of the WIG and related devices to patent disclosure. Here some latitude was given as to what might be considered a WIG in that many boats and craft with air-displacing or lifting features were included. Generally, only those patents are included in which the inventor states in some manner that his invention may be fully or partially airborne due to certain shapings of the hull or winged surfaces. Certain boating or flying systems have been listed which this author feels indicate distinct means for accomplishing close surface flight or transport. The collection of patents cited here should not be regarded as a substitute for final or professional patent search, however.

Because of the large number of references listed, it was felt that the reader might have difficulty selecting the references of interest to him. Therefore, a supplementary bibliography (Appendix A) has been prepared, the references of which are themselves bibliographies or reports of special importance, arranged by subject matter. This appendix should be

considered as an extension of the theme of this bibliography and should direct the reader to related areas of interest.

These areas of extended interest are described herewith:

1. Aerodynamics and Hydrodynamics of Seaplanes

If one considers the ram wing operating from the water surface as a special case of the seaplane, then many of the hydrodynamic performance reports and information may be of immediate value.

2. VTOL/STOL Aircraft

The bibliographies list many references for ducted fan, deflected slipstream, fan-in-wing, etc., all of which are aircraft operating in ground effect. The ability of most of these aircraft to hover excludes their reference from the body of this bibliography.

3. Ground Effect Machines

As the WIG may certainly be considered to be one of the family of GEM's, then many of the problems and comparisons associated with other GEM systems may have application to the WIG.

4. Hydrofoils

Bibliographies are, in part, included here for their general interest; but more in particular, for certain theoretical considerations in which the hydrofoil operating in the proximity of the free air or water surface may represent applicable problems as encountered also by the WIG when operating close to a free surface.

5. Interface Meteorology and the Katzmayer Effect

The operational domain of the applied WIG will, in all probability, be over the water. This surface is seldom smooth. The effect of the wind is to produce waves; and hence, the medium (interface) in which the WIG will operate is not stable or rigid, but subject to irregular motion and oscillation. Hence, it will become necessary to understand the effect of this disturbance on the aerodynamics of the WIG. To this end, there are included several references with bibliographies on wind-wave studies and also references on the Betz-Knoller or Katzmayer effect. These latter effects concern the apparent change of lift and drag of an airfoil when impressed in such a fluctuating airstream.

6. Automobile Wind Tunnel Air Resistance Testing

References are included in the supplementary bibliography for those interested in problems which are suggested by the aerodynamic characteristics of wheeled vehicles moving over the ground surface.

7. Raimondi Effect

A primary source with references is included in Appendix A covering the Raimondi Effect. This effect explains the attraction of a circulation towards a boundary or surface and this material may complement certain theoretical considerations of the WIG.

8. Miscellaneous

PRESENTATION OF RESULTS

The references are arranged in an alphabetical order by the principal author's last name. In the case of more than one entry by an author, it will be found that his earliest contribution will appear first in the listing. In the instance where a group or company is responsible for the authorship of a publication, then the known name of the organization will be alphabetically placed. References consisting of comments or photographs are entered into the listing alphabetically, usually by subject matter or description.

A series of tables is included which provide an insight into the references. With these tables it becomes possible to search out a combination of subjects or interests to a number of specific sources. By scanning across the appropriate columns of descriptors, the scope of a particular reference may be quickly revealed and understood.

Table 5 describes the structure or presentation of a reference. This usually will be found helpful in assessing the extent of detail presented and the availability of the source. Note that there is one category in which the references may be cited as generally unavailable. This category is intended to single out references which have security classification or are generally considered to contain material proprietary to a particular company. This group also covers papers that are currently unpublished for one reason or another; but which probably could be obtained by some effort. Another category is cited in which the references were not examined by the author because of their immediate unavailability

and the lack of time required to search them out. The reader may therefore only know of their existence, sense their content from the title and hope to have better access to sources in this last category.

CONCLUDING REMARKS

Upon reviewing the bibliography, it was decided that the tabulated reference listing against descriptors was an excellent means to understand the content of a source which dealt with matters of experiment and application and, generally, for most works of a theoretical nature. The review of experimental work on wings in ground effect from the initial tests by A. Betz (1912) to the present date reflects only a few narrow avenues of interest in spite of the bulk of material available. Generally, the experimental data available fall into these groups:

1. Exploratory tests.
2. Tests made to substantiate theoretical investigations.
3. Forces and moments on aircraft wings during landing and taking off.
4. Renewed investigations in the light of current applied ram-wing interest.

However, many of the theoretical works were felt to be of such a basic and often unique nature that the tabulation often could not express the intent or method of the author. To clarify the theoretical background and to suggest a directed evolution of WIG theory, it was decided to abstract, at this point, all theoretical and truly contributory papers available in a chronological manner. Those theoretical papers concerned with the wind-tunnel ground interference correction have not been abstracted here.

A review in Appendix B of the theoretical treatment of WIG's indicates that the authors working in the last ten years apparently were not aware of the magnitude of the field as reported here. Now that the present review is available, it could prove the basis for much fruitful work, resulting from the cross-fertilization of individual ideas presented herein.

A synthesis of the available information on WIG's should be made. In particular, it is important to make an assessment of the ranges of

the ground distance parameter h/C for which each three-dimensional theory holds. The closer to the ground one wishes to consider, the more singularities are required. Also, very close to the ground, linearization is not permissible, whereas this is permissible for the unbounded case.

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APPENDIX A

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APPENDIX B

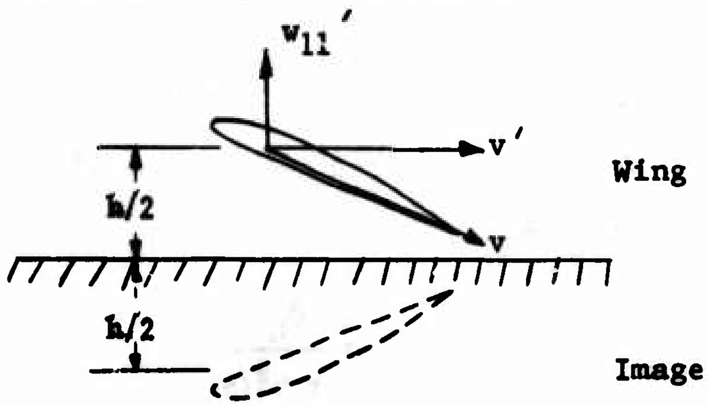
SURVEY OF THEORETICAL PAPERS

Selected theoretical papers listed in the main bibliography are discussed briefly. Only the number of the entry and the author's name are used to identify each paper.

[32] Betz - In many bibliographies, this paper is credited as being the first "theoretical" study of airfoils in ground effect. This is not the case; the paper is limited to reporting experimental results of drag reduction and lift increase associated with the ground effect. It is, in fact, the first experimental report on the subject.

[31] Betz - In this paper, the analogy between a wing in ground effect, which can be replaced by a wing and the image wing with respect to the ground, and a biplane wing is recognized. The paper has, otherwise, only historical interest, since it precedes the publication of Prandtl's lifting-line wing theory by five years.

[352] Wieselsberger - This is the classical elementary treatment of the effect of the ground on a wing of finite span which can be found in most books on aerodynamics. One replaces the ground by an image wing, symmetrical to the true wing with respect to the ground, and then calculates the interaction of the image wing and the actual wing by means of Prandtl's lifting-line theory. The calculation is similar to that used to determine the drag of a biplane from the drag of a monoplane.



The resulting direction of the flow on the wing (indicated by v') is found by the geometric addition of the original direction of the velocity v and the vertical velocity w_{11}' due to the image wing. The induced drag near the ground is smaller than at a higher altitude, since w_{11}' increases to a maximum from a value of zero far from the ground.

The change in drag due to the ground is given by:

$$W' = - \int_{-b/2}^{b/2} \frac{w_{11}'}{v} \, dA \quad ,$$

where w_{11}' is given, from Prandtl's theory, by:

$$w_{11}' = \frac{2A}{\pi \rho v b^2} \cdot z$$

where A is the lift, v is the velocity, b is the span, and z is the distance between the two wings, which is related to h/b.

The value of the above integral can be determined numerically for different values of h/b and the result expressed by the influence coefficient σ , such that

$$\Delta C_D = - \sigma \frac{C_L^2}{b^2/S}$$

where S is the wing area and C_L and C_D are the lift and drag coefficients, respectively.

The change of angle of attack of the wing, due to the ground, can be expressed as

$$\Delta \alpha = - \sigma \frac{C_L}{\pi \, b^2/S}$$

Therefore, the influence of the ground on the wing of finite span is equivalent to an increase in aspect ratio. Calling AR' the aspect ratio near the ground and AR that far from the ground, one has:

$$AR' = \frac{AR}{1-\sigma}$$

Later investigators have devised other empirical formulas relating σ to h/b; for example,

$$\sigma = \frac{1}{1 + 5.3\,\frac{h}{b}} \quad , \quad \text{for } \frac{1}{15} < \frac{h}{b} < \frac{1}{4}$$

[125] Glauert - Glauert modifies Wieselsberger's theory by assuming that the velocity induced by the image wing on the real wing must be measured at the center of the wing, but locates the bound vortex of the image wing at the center of pressure of the wing. There results a correction term on the circulation as compared with Wieselsberger's case.

[35] Bonder - This is the first sophisticated theoretical investigation of flight near the ground. It makes a conformal transformation of two opposite wing profiles separated by a plane of symmetry (the ground) into two adjacent cylinders. The calculations are complicated and do not lead to practical numerical expressions. A similar technique was used later on by Müller (Reference 227) and Tomotika (Reference 325).

[227] Müller - A series of lenticular or airfoil shapes, symmetrical with respect to a plane simulating the ground, are transformed into circular cylinders, as was done in Reference 35 by Bonder, using two successive conformal transformations (the conformal mapping theory of Ferrari). The lift over the airfoil is calculated and leads to results apparently difficult to reconcile with experiments; e.g., that the lift decreases when the airfoil is close to the ground.

[279] Rosenhead - The problem of continuous flow past a flat plate of infinite span between plane parallel walls is solved exactly, using all the mathematical apparatus later used by Tomotika and others in the ground effect problem, in which one of the two parallel walls is removed. The paper is therefore of interest because of its mathematical foundation, not because of its results.

[311] Tani

1. Two-Dimensional Analysis - A plane wing having infinite span and chord c is placed near the ground, at an angle of attack α , free-stream velocity V, and the height of the quarter-chord point H.

The circulation around the wing is given in the form:

$$\Gamma = n \pi V c \sin \alpha_o$$

where n represents the change in circulation compared with that of a wing placed far above the ground.

The chordwise vorticity distribution is assumed (following Birnbaum) to be:

$$\gamma = a_o\sqrt{\frac{1-\xi}{1+\xi}} + a_1\sqrt{1-\xi^2} + a_2 \xi \sqrt{1-\xi^2}$$

The terms a_o, a_1, a_2 are determined from the assumption that the velocity normal to the chord is zero at three points:

$$\xi = -1,\ 0,\ \text{and}\ 1$$

To satisfy the boundary condition at the ground plane, an image wing is introduced with vorticity distribution:

$$\gamma' = -a_o\sqrt{\frac{1-\xi'}{1+\xi'}} - a_1\sqrt{1-\xi'^2} - a_2 \xi'\sqrt{1-\xi'^2}$$

from which n can be calculated as:

$$n = \frac{a_o}{2V \sin \alpha_o} + \frac{a_1}{4V \sin \alpha_o}$$

2. Three-Dimensional Analysis - The velocity on the wing due to the wing itself is calculated assuming an elliptical circulation distribution, while the velocity induced by the image wing is calculated by assuming a uniform circulation distribution across the image wing.

[326] Tomotika - This is the first attempt at a fairly rigorous mathematical treatment of the problem of the calculation of the lift of a flat plate placed in a free stream, in the neighborhood of a wall.

The system of the flat plate at an angle of attack and the ground is transformed by three successive conformal transformations (previously used by Rosenhead (Reference 279) into a ring region, in which an analytic function satisfying the boundary conditions of the problem can be found, using one of Villat's formulas (derived in 1912). The conformal transformations involve: first, the Schwarz-Christoffel method; second, the Weierstrass $\wp$-function; and, third a logarithmic transformation. Once the complex velocity potential is found, the lift is calculated by means of Blasius' formula. The answer is obtained in series form.

[320] Tomotika - The problem treated in this paper is mathematically the same as that of Reference 326; however, the ground is above rather than under the wing. The problem is of some academic interest.

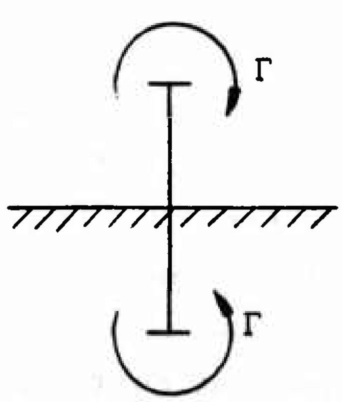
[78] Dätwyler - Dätwyler solves several theoretical problems. One of these is that of the two-dimensional flat plate touching the ground on one side. The solution is obtained by conformal mapping, using the Schwarz-Christoffel method. He calculates the lift on the plate directly, without needing Blasius' formula. Another problem is that of the plate at right angles to the flow with an edge close to the ground. Finally, Dätwyler gives an approximate method of calculation of the lift for a symmetrical wing which uses the image theory.

[319] <u>Tomotika</u> - Following some of Dätwyler's experimental results (Reference 78), Tomotika found it necessary to make additional numerical calculations in the theory of Reference 326, to verify Dätwyler's results. It was found that the Tomotika theory was in agreement with these results.

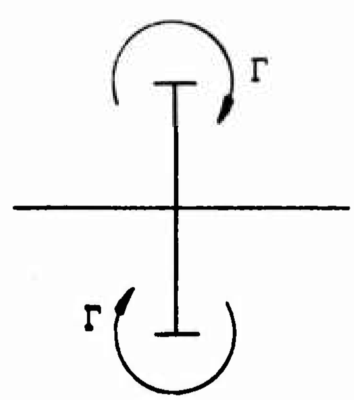
[52] <u>Carafoli</u> - The author uses a simple method (two-dimensional), replacing each wing by a bound vortex and giving the complex potential for the two vortices. The relative flow velocity at the wing can be calculated, showing a decrease in circulation, due to the decrease in velocity at the wing.

This analysis, like Müller's, is contrary to experimental evidence. No change in drag is predicted. Replacement of the airfoil by a line vortex is justified only in the case where the distance between the airfoil and the ground is too large to be of practical interest.

[341] <u>von Kármán and Burgers</u> - The interaction of a single vortex line of infinite extent representing a wing with a free boundary is treated by applying the condition that the pressure at all points of the boundary has the same value. The condition is that W_x, horizontal velocity at the boundary, is equal to zero. This is accomplished by taking the image vortex and changing the direction of its circulation, as compared with the solid boundary case.



Fixed Boundary



Free Boundary

[321] Tomotika and Imai - A rigorous mathematical analysis is developed for the hydrodynamical problem of calculating the lift on a flat plate placed in a two-dimensional continuous stream of fluid which is bounded by a free surface on the lower side of the plate. The conformal mapping formulation of the problem is exactly the same as for the basic problem of Reference 326, since for both a free and a fixed surface the stream function is constant. In the latter case, for further calculations, one uses the fact that the angle between the fixed surface and the direction of the velocity is known. In the former case, it is known that the magnitude of the fluid velocity along the free surface is constant and equal to the free-stream velocity.

Numerical calculations for this problem are very long and tedious. It is shown that, for values of angles of attack from 10° to 15°, the lift is increased a small amount because of the presence of the free surface when the distance of the plate from the surface is of the same order of magnitude as the breadth of the plate.

[322] Tomotika and Imai - The moment of the fluid pressure acting on a plate is calculated when the plate is placed in a semi-infinite stream bounded by an infinite wall on the lower side of the plate. Only the flow with circulation around the plate is considered, and the value of the circulation is so chosen that the flow leaves the trailing edge of the plate smoothly. The conformal mapping calculation is the same as in Reference 326. The moment is calculated using Blasius' formula.

These theoretical results lead us to expect that:

1. The center of pressure of a plane airfoil moves toward its midpoint for any value of the angle of attack as the airfoil approaces the ground.

2. The moment of the resultant pressure about the midpoint of the airfoil decreases because of the interference of the ground when the angle of attack assumes large values; but, on

the contrary, when the angle of attack is small, the moment increases because of the effect of the ground as the airfoil approaches sufficiently near the ground.

[324] Tomotika and Imai - In this paper, Dätwyler's method of calculating the lift and the moment of an airfoil when it touches the ground with its trailing edge is re-derived. It is also shown that Dätwyler's analysis is a limiting case of the analysis of Reference 326.

[313] Tani, Taima and Simidu - This paper is an extension of the work of References 254, 255, and 256. It treats both two- and three-dimensional cases. In the two-dimensional case, a chordwise distribution is assumed, as in References 254, 255, and 256. The aim of the study is to find out (a) the effect of bound vortices of the image wing (these were disregarded in References 311 and 352, for example) and (b) the effect of wing thickness. It is reasoned that the vorticity distribution of Reference 311 is equivalent to the introduction of a point-vortex of circulation Γ and a component doublet of vertical moment $\Gamma \sin \theta$. Therefore, the thickness can be expressed as a component doublet of longitudinal moment $\Gamma \cos \theta$. Further one has:

$$\Gamma \cos \theta = -0.6\, V e c^2 \quad ,$$

where e is the maximum thickness in terms of the chord. The thickness effect turns out to correspond to a decrease $-\kappa e$ in the effective angle of attack. In the three-dimensional case, the effect of the finite length of the trailing vortices of the image wing is considered, as well as that of the bound vortices. A formula is given for summarizing the effect of ground on the effective angle of attack for a wing of finite span.

[327] Tomotika, Tamada, and Saito - This paper is a further exploitation of References 326 and 320, where the attention is focused on the variation of circulation with ground distance rather than on the variation of lift. It is found that the

circulation is greatly affected by the presence of the ground. Comparing the curves for the circulation with the corresponding curves for the lift found in References 326 and 320, it is found that the variation of the lift of the plane airfoil due to the ground is, for the most part, attributable to the variation of the circulation of the airfoil.

[152] <u>Hudimoto</u> - The problem of the effect of ground interference upon an airfoil with a circular-arc section when the circle of this airfoil intersects or touches the surface of the ground is treated. By two successive conformal transformations, involving the Weierstrass $\wp$ and ζ functions, the region outside the circular arc and the straight line is transformed into a rectangle. Then the velocity of the flow of the perfect fluid is determined; and hence, the lift and the moment of the lift acting on the airfoil are calculated by Blasius' formula.

[323] <u>Tomotika and Imai</u> - This paper complements and extends earlier work by de Haller, "La Portance et la Trainée Induite Minimum d'une Aile au Voisinage du Sol" [89].

The problem is the same as that of Reference 152. However, because the trailing edge of the airfoil touches the ground, the conformal transformation is much simpler. One can use the Schwarz-Christoffel method. Thus, the expression for the lift and moment can be found rigorously. By carrying out detailed numerical computations, the effect of camber on the ground effect can be assessed. It is found that the ground effect is not greatly modified by the camber of the airfoil. Hence, the results for plane airfoils seem to be applicable without serious error.

[127] <u>Green</u> - The forces which are acting on a circular-arc airfoil when it is in any position near a plane wall are obtained. This is exactly the same problem as that of Reference 152, except

that Reference 152 is limited to the case when the circle carrying the circular arc intersects the ground plane. (This is the only practical case, anyway.) However, the conformal mapping solution is different, and Green does not refer to Reference 152.

The complex velocity potential is calculated by Green in the same way as in Reference 326; i.e., using the Schwarz-Christoffel method, followed by the application of another transformation involving the Weierstrass $\wp$-function. Green found that additional conformal transformations useful for the problem had been obtained in 1924 by Hodgkinson and Poole. Green is able to solve, analytically, the most general case of the circular airfoil near the ground and to prove that both References 152 and 326 were limiting cases of his general case.

[329] Tomotika, Urano, and Hasimoto - This paper is a follow-on to Reference 323; there is no additional theory. The purpose of the paper is to show that, in Reference 127, Green had arrived at wrong numerical results concerning lift and moment coefficients. It is shown numerically that, for small angles of attack, lift and moment coefficients of a circular airfoil are greater when the airfoil touches the bounding wall than when it is far from it. Green had been claiming the opposite result.

[128] Green - The problem of the fairly general airfoil in the presence of a plane is treated, using the simplest possible approach. The method is original and has been used by many subsequent authors, and will therefore be summarized here.

The airfoil in the complex Z-plane is obtained from a straight line of length 2n in the complex ξ-plane by means of the transformation:

$$Z = e^{-i\xi} \sum_{n=o}^{\infty} a_n e^{in\xi}$$

The airfoil is placed in the vicinity of a plane rigid wall. The fluid at infinity flows parallel to the wall with a constant velocity c, and there is a circulation $\varkappa = 2n\,A_o$ around the airfoil.

A suitable complex velocity potential which makes the boundary wall a streamline was found by Green to be:

$$W = cZ + iA_o \{\log Z - \log(Z + 2ib)\}$$
$$+ \left\{ \sum_{n=1}^{\infty} \frac{A_n}{Z^n} + \frac{\bar{A}_n}{(Z + 2ib)^n} \right.$$

where $\bar{A}_n$ denotes the complex conjugate of A_n .

Forces and moments can be computed by Blasius' formulas. The coefficients A_n are determined by satisfying the boundary conditions at the surface of the airfoil. The circulation is determined in the usual way, by assuming a stagnation point at the trailing edge. The circular-arc airfoil is treated as a special case. The numerical solution for the lift on the airfoil is given in the form of a series, for which only the first three terms could be obtained, so that results must be accepted with caution.

[328] Tomotika, Tomada, and Umemoto - The paper is concerned with the same problem as is treated in References 127 and 152: lift and moment of circular airfoil placed in a stream bounded by a plane wall. The study is more thorough than that of Green (Reference 127) and follows the mathematical outline of Hudimoto (Reference 152). It is found that, when the camber of the airfoil is small, the effect of the wall on the lift and moment is similar to that for an airfoil in the form of a flat plate; namely, as the airfoil approaches the wall, the lift and moment coefficients first decrease and then increase to values which are greater than the corresponding values for a circular-arc airfoil in an unlimited stream.

[325] Tomotika, Hasimoto, and Urano - The forces acting on an airfoil of approximate Joukowski-type in a stream bounded by a plane wall are calculated by using the method of images and a conformal transformation technique. The airfoil and its image are transformed into two cylinders, as was previously done by Müller (Reference 227). In other words, the cylinders are transformed into a rectangle by means of the Weierstrass $\wp$-function.

The paper is more precisely concerned with a study of the changes caused by the thickness of an airfoil on the ground effect than upon its lift. It is found that, at small angles of attack, the lift on the airfoil is generally increased by the presence of the ground, but the rate of increase of the lift with distance above the ground becomes smaller as the thickness of the airfoil increases.

[117] Fujikawa - In this paper, the lift on the symmetrical Joukowski airfoil of small thickness in the presence of a plane rigid wall is obtained in the form of a power series, limited to the first five terms, for the purpose of determining the manner in which the ground effect on the lift of an airfoil is modified by its thickness. The calculation of the lift is carried out, using Green's analysis of Reference 128.

It is found that, at small angles of attack, the wall effect on the lift is quite similar to that in the case of a plane airfoil and further, it is found that, for a given distance of the airfoil from the wall, the wall effect on the lift decreases as the thickness increases, even for small values of the angle of attack.

[118] Fujikawa - Green's method of Reference 128 is applied to the evaluation of the lift acting on a circular-arc airfoil in the presence of an infinite plane rigid wall. The expression for the lift is obtained in the form of a power series. After performing detailed numerical calculations, a discussion is presented on the manner in which the ground effect on the lift of an airfoil is modified by its camber.

It is found that, in accordance with the prediction made by Tomotika (Reference 328), as the arc-airfoil of sufficiently smaller camber approaches the wall, the lift first decreases and then tends to increase to values which are greater than the corresponding values for the same arc-airfoil in an unlimited stream, especially when the angle of attack is small. It is also found that the rate of increase in the lift becomes smaller as the camber of the airfoil increases.

[23] Bagley - A simple method of calculating the pressure distribution in incompressible flow on two-dimensional airfoils of arbitrary section near the ground is developed. The method used is essentially that of Tani (311 and 313); but an extended source distribution is used to represent the airfoil and its image instead of the two doublets used by Tani. A distribution of vortices on two parallel lines is used to represent the airfoil at incidence and its image. The velocity field due to such a distribution has been tabulated by Küchemann and Weber and is also presented in this paper. The closed-form solution of Reference 325 indicates that the velocity distributions agree within about 5 percent. Comparison with a series of experimental measurements on a 10-percent-thick RAE 101 airfoil at distances between 0.5 chord and 0.73 chord from the ground also shows that good agreement is obtained, provided allowance is made for the boundary layers on the airfoil and on the ground board.

[38] Braunss, G. and Lincke, W. - This paper appears to be a summarized version of a publication of the same title prepared in 1960 as a report of the Proceedings of the Aeronautical Institute of Darmstadt [39]. The authors treat the problem of the aerodynamic characteristics of a flat plate near the ground immersed in an incompressible two-dimensional flow. The problem has been treated, using conformal mapping techniques, in References 326, 322, and 324. It is treated here using Munk's classical thin airfoil theory; i.e., distributing singularities, in the form of a vortex distribution of strength $\gamma(x)$ along the flat plate.

The relationship between the induced normal and tangential velocities V_n and V_t at a point x_o on the plate and the vortex strength $\gamma(x)$ is as follows:

$$V_n(x_o) = \frac{1}{2\pi}\int_o^1 \gamma(x)\left[\frac{1}{x_o - x} + \epsilon(x,x_o)\right] dx$$

$$V_t(x_o) = \frac{1}{2\pi}\int_o^1 \gamma(x)\ \tau(x,x_o)\ dx$$

where

$$\epsilon(x,x_o) = \frac{2h_o \sin\alpha - x_o + x\cos 2\alpha}{(2h_o \sin\alpha - x_o + \cos 2\alpha)^2 + (x\sin 2\alpha - 2h_o \cos\alpha)^2}$$

and

$$\tau(x, x_o) = \frac{x\sin 2\alpha - 2\,h_o \cos\alpha}{(2h_o \sin\alpha - x_o + x\cos 2\alpha)^2 + (x\sin 2\alpha - 2h_o \cos\alpha)^2}$$

where the length of the plate is unity. The coordinate along the plate measured from the leading edge is x, the angle of attack is α, and the distance between the ground and the quarter-chord point is h_o .

If V_∞ is the free-stream velocity, the two boundary conditions on the plate can be written as:

$$V_\infty \sin\alpha + V_n(x_o) = 0$$

$$V_\infty \sin\alpha = \frac{1}{2\pi}\int_o^1 \gamma(x)\left[\frac{1}{x_o - x} + \epsilon(x,x_o)\right] dx$$

Letting

$$x = \tfrac{1}{2}(1 - \cos\phi)\ ;\ x_o = \tfrac{1}{2}(1 - \cos\psi)$$

the vortex strength is written, classically:

$$\gamma = 2\,V_\infty\left[(A_o + \sin\alpha)\frac{1 + \cos\phi}{\sin\phi} + \sum_{\nu=1}^{n} A_\nu \sin\nu\phi\right]$$

Hence, by substitution:

$$A_o \left[1 + Q(\psi)\right] - \sum_{\nu=1}^{n} A_\nu \left[\cos \nu\psi - T_\nu(\psi)\right] = -\sin \alpha \, Q(\psi)$$

where

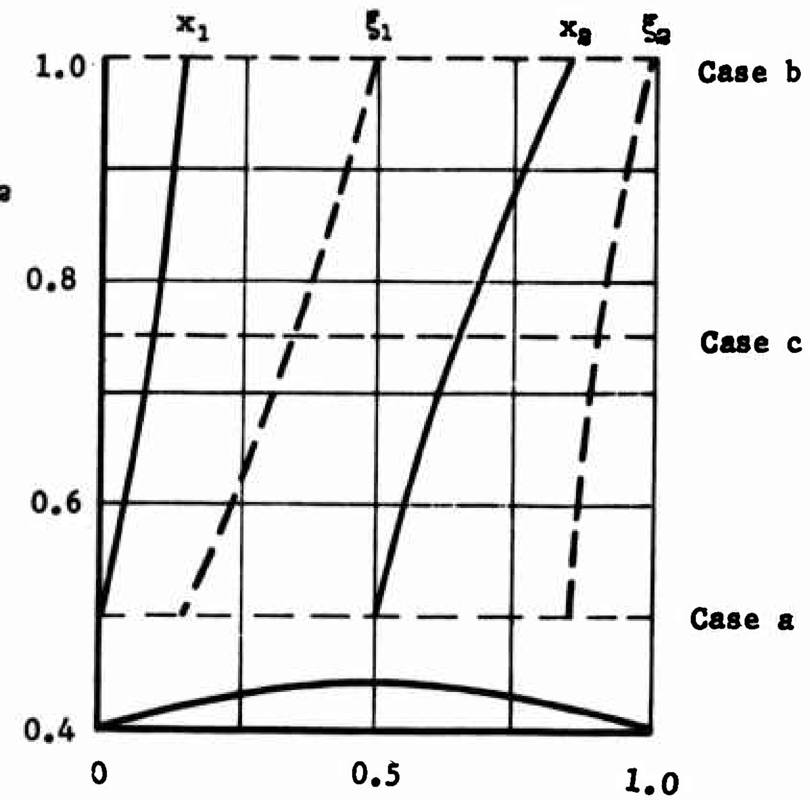
$$Q(\psi) = \int_0^\pi \epsilon(\phi, \psi)(1 + \cos \phi) \, d\phi$$

$$T_\nu(\psi) = \int_0^\pi \epsilon(\phi, \psi) \sin \phi \sin \nu\phi \, d\phi$$

Using the proper approximate expression for $T_\nu(\psi)$, one can calculate the coefficients A_n by Fourier series integration. Computers are useful for numerical solutions.

[1] Ackermann, U, and Bock, G. - In Reference 38, a two-dimensional airfoil near the ground is represented by a continuous vortex distribution. This mathematical representation does not allow for a tractable extension to the three-dimensional case. The purpose of the present paper is, therefore, to simplify as much as possible the representation of an airfoil in ground effect by investigating the correctness of the approximation made in replacing the wing section by a model of two vortices, which gives exactly the lift and the center-of-pressure position of a plate with incidence and parabolic camber in free two-dimensional flow. By means of this simple model, and using classical thin airfoil theory, the flat plate is investigated in two-dimensional flow near the ground. Numerical calculations were made for three different vortex control point locations shown in the figures. Here ξ_1, and ξ_2 are the distances of the control points and x_1 and x_2 are the distances of the vortices from

the leading edge of the airfoil (the chord length is unity). In the three cases, designated a, b, and c, the values of $\phi \equiv x_1 + x_2$ are 0.5, 1.0, and 0.75, respectively.



Distance from L. E. of Airfoil

A comparison between the results of the calculations with those of Reference 326, indicates that the two-vortex approximation using $\phi = 0.75$ is very useful in a wid^ domain of applications.

[207] Malavard, L. - Two-dimensional flows around airfoils placed in the immediate vicinity of the ground are analyzed theoretically by means of the electric analogy. The advantage of the electrical analogy method is that is allows ^ rigorous solution of the problem, which is necessary because Malavard feels that the assumptions of small disturbances in which second-order perturbation terms are disregarded does not hold very near to the

ground. He states that the theory of Reference 305 is not valid for this case. He proves it as follows:

The perturbation velocity along the ground is given by:

$$u_{1g} = -\int_{-\infty}^{+\infty} (V_g - V_\infty)\, dx = \int_{-\infty}^{+\infty} u_g\, dx$$

where

V_∞ free-stream velocity

V_g resultant velocity along the ground

x coordinate parallel to the ground

$$u_g = V_g - V_\infty$$

Now, the lift coefficient on the airfoil is given by:

$$C_L = C_{L_\Gamma} - \int_{-\infty}^{+\infty} \left(\frac{u_{1g}}{V_\infty}\right)^2 d\left(\frac{x}{c}\right)$$

where

$$C_{L_\Gamma} = -\frac{\Gamma}{V_c c}$$

is the circulation lift coefficient.

In classical wing theory, one assumes $C_L = C_{L_\Gamma}$. Malavard calculates the value of the disregarded integral involving u_{1g} in the case of a constant vorticity distribution along a segment of length c, parallel to and a distance h from the ground, as well as for various combinations of source and sink distributions, and shows that this term can reach 20 percent of the C_{L_Γ} term at a height-chord ratio of 0.05.

Different methods of using the rheoelectrical analogy are described, which make it possible to simulate in an electric tank either the velocity potential or the stream function, or the argument-function, or the logarithmic potential of the flow.

Applications to convex-plane airfoils, Clark Y airfoils with or without blowing, and flat plates with flaps are indicated.

The results obtained show that:

a. The lift of airfoils whose lower surface is plane and parallel to the ground generally increase as the distance to the ground becomes smaller.

b. The effect of a light blowing at the trailing edge is likely, owing to the blocking effect it generates, to improve the lift considerably.

c. The effect of the ground on an airfoil with a down-washed flap is obviously adverse.

[193] Licher, R. M. - The effect of the ground on the lift of a wing in ground effect is approximated theoretically by means of a singularity method, using networks of finite-strength bound and trailing vortices. For the two-dimensional flat-plate wing, comparison made with the known exact solution of Reference 326 indicates that a set of finite-strength bound vortices can adequately represent the lift of the wing near the ground; however, the number of vortices used must vary with the distance above the ground, increasing when one comes closer to the ground.

For the cambered two-dimensional wing, two different arrangements of the bound vortices are considered; these are believed to bracket the correct results. This method is similar to that used in Reference 1.

For the three-dimensional wing, several networks of bound and trailing vortices are examined and compared with Tani's method (References 311 and 313). One calculation includes the twist and taper; sweptback and delta wings cannot be analyzed by that method.

[315] Thomas, F. - A method based on the extended lifting-line theory is given, which permits the calculation of the lift distribution near the ground for airfoils of arbitrary planform, particularly

sweptback and delta wings. The report is therefore, for the three-dimensional case, an extension of Reference 193. The ground effect is taken into account by the reflection method. The velocities induced by the reflected airfoil at the actual airfoil considered are calculated in accordance with a method given by K. Gersten (1957 Jahrbuch der Wissenschaftliche Gesellschaft für Luftfahrt, pages 172-190).

The theoretical results are well confirmed by comparative measurements on a sweptback wing and a delta wing in the Brunswick wind tunnel. Theory and experiment indicate an increase in the lift curve slope and a decrease in the induced drag near the ground. Apart from these comparative measurements, ground effects on the position of the aerodynamic center, the maximum lift, and the flap effectiveness are investigated.

[63] Chaplin, H. R. and Masters, L. W. - The induced drag of several types of wings in ground effect is calculated theoretically, in an extension of Wieselsberger's original method (Reference 352), by setting up the potential problem in the Trefftz plane and solving it using the rheoelectrical analogy. The shed vortex system is assumed to trail straight behind the wing, and Teledeltos conductive paper is used as the working medium.

For the case of uniform downwash, span-loading distributions and effective aspect ratio are measured, as functions of height/span ratio, for plane wings, certain end-plated wings, and for a wing of which the lateral cross-section is a circular arc with its center lying at the ground surface. The results indicate that the use of end plates to reduce the ground clearance is relatively ineffective compared with reducing the ground clearance along the whole span, from the standpoint of increase in effective aspect ratio.

[356] Williams, P. G. - The lift of a two-dimensional wing located in ground proximity with a jet flap impinging vertically downward, with a large enough momentum jet coefficient that the deflection of the jet can be disregarded, is solved

mathematically by conformal mapping. The wing is regarded as a thin plate at zero incidence, and the jet as a solid boundary perpendicular to the wing connecting the trailing edge to the ground. This potential flow problem, the flow of an obstacle in the shape of an inverted L projecting from the ground, was solved by Darwin in 1945, in connection with the design of minimum-drag tip fins. The form of the solution follows.

The transformation reads:

$$z = d \frac{2K}{\pi}\left[Z(\zeta) - \frac{a \text{ cn } \zeta \text{ dn } \zeta}{1 - a \text{ sn } \zeta}\right]$$

where d is the vertical distance of the wing from the ground, a is a parameter, and standard notation is used for the Jacobian elliptic functions (K is the complete elliptic integral of the first kind and Z the Jacobian Zeta function), z is the complex variable in the physical plane, and ζ is the complex variable in the transformed plane.

The complex potential is:

$$w = -Ud \;.\; \frac{2K}{\pi}(k^2 - a^2)^{\frac{1}{2}} (1 - a^2)^{\frac{1}{2}} \frac{\text{sn } \zeta}{1 - a \text{ sn } \zeta}$$

where U is the free-stream velocity and k is the modulus of the elliptic functions.

Using conventional techniques, the lift can be expressed in terms of tabulated elliptic integrals. The formulas are evaluated to obtain a graph of the pressure lift as a function of height above the ground. These data are compared with previous approximate and experimental results.

[332] Toussaint, A. - Two-dimensional wings in ground effect are studied by replacing the ground by the image wing and considering the system of real wing and image wing as a biplane. The wings are assumed to have thickness and camber, and are at an angle of attack. Aerodynamic forces on the biplane are found by conformal mapping.

The results show that, at zero angle of attack, for a symmetrical airfoil, the wing in ground effect has a negative lift, which depends mostly upon the thickness of the wing. Therefore, the angle of attack corresponding to zero lift is positive in ground effect and decreases to zero outside of ground effect. The second effect of the ground is to increase the slope of the lift curve.

Based on the results of the conformal mapping theory, Toussaint proposes the following formulas to represent the change in zero-lift angle due to ground effect and the lift curve slope, for a symmetrical airfoil, 13 percent thick:

$$100 \; \Delta C_{L_{\alpha=0}} = -0.62\left(\frac{c}{h}\right)^{2.5}$$

$$\left(\frac{dC_L}{d\alpha}\right)_h = \left(\frac{dC_L}{d\alpha}\right)_\infty + 0.6\left(\frac{c}{h}\right)^2 - 0.025\left(\frac{c}{h}\right)^2 \alpha$$

The expression for the lift is then given by:

$$100 \; C_{L_h} = 100 \; C_{L_\infty} + \left(\frac{c}{h}\right)^2 \left[0.6 \; \alpha - 0.025 \; \alpha^2 - 0.62 \sqrt{\frac{c}{h}}\right]$$

In the above equations, the terms are defined as follows:

- c airfoil chord
- h height above ground (measured from mid-chord)
- α angle of attack, in degrees
- C_L lift coefficient

In a later publication (Reference 334), Toussaint extends the above formulas to any airfoil.

[255], <u>Pistolesi, E.</u>
[256] Two- and three-dimensional cases are treated successively. The three-dimensional method is applied as follows:

a. Calculate the circulation around the wing as a function of the velocity (resultant of the velocity at infinity and the induced velocity) at a distance of one-quarter chord from the trailing edge (point k). The lift is obtained by multiplying the component of velocity normal to the chord line by $\ell c'$, where ℓ is the chord length and $c' = \frac{1}{2} \cdot \frac{dC_L}{d\alpha}$. (In practice $c' \approx \pi$.)

b. Replace the wing, for calculating induced effects and lift, by a vortex located at the center of gravity of the circulation; or place the vortex at a distance $\ell/4$ from the leading edge (point I), while adding there the proper doublet. For the flat plate, the doublet strength is zero, and the wing is replaced by a single bound vortex.

To calculate induced effects, one initially disregards angle of attack effects; they can be accounted for, in an approximate manner, later on.

In accordance with the above scheme, one calculates the normal velocity V_n at point k:

$$V_n = V_o \sin \alpha + \frac{\Gamma}{2n} \frac{\ell/2}{4h^2 + \ell^2/4}$$

hence

$$\Gamma = n \ell V_n \alpha = \Gamma_o + \Gamma \frac{\ell^2/4}{4h^2 + \ell^2/4}$$

or

$$\Gamma = \Gamma_o \; (1 + \ell^2/16h^2)$$

Now the velocity at point I is:

$$V_o - \frac{\Gamma}{4nh}$$

Hence, the lift is given by:

$$L = \rho \Gamma \left(V_o - \frac{\Gamma}{4\pi h}\right)$$

or

$$L = \rho\pi \ell V^2 \sin \alpha \left[1 - \frac{\ell}{4h}(1 + \ell^2/16h^2) \sin \alpha\right]\left[1 + \ell^2/16h^2\right]$$

$$\frac{L}{L_o} = \left[1 - \frac{\ell}{4h}(1 + \ell^2/16h^2) \sin \alpha\right]\left[1 + \ell^2/16h^2\right]$$

These results compare relatively well with those of Tomotika (Reference 326).

These formulas are extended by Pistolesi to include the effects of angle of attack (in the calculation of V_n) and of airfoil curvature. Better agreement with Tomotika's results is then found.

For the three-dimensional treatment, Pistolesi simplifies the problem by disregarding tip vortices and replacing the wing and its image by a horseshoe vortex distribution, which assumes uniform spanwise lift distribution. He finds qualitative agreement with experiments; in particular, the increase in lift decreases, when the incidence increases, until it becomes zero.

Pistolesi suggests that the method can be improved to represent elliptical spanwise lift distributions by using Ferrari's conformal mapping method.

[308] Strand, T., Royce, W. W., and Fujika, T. - Three problems relating to the aerodynamic lift theory of high-speed air-cushion vehicles are discussed.

a. Two-dimensional airfoil theory

The ground is replaced by the image airfoil (zero angle of attack). The airfoil and its image are replaced by a continuous distribution of sources and vortices extending from

leading to trailing edge along the line $y = \pm h$ (where h is the distance to the ground). The velocity components are calculated in the conventional manner. The boundary condition at the airfoil is expressed as:

$$\left.\frac{dy}{dx}\right|_{y=h} = \frac{v}{V_o + u}$$

where

x	coordinate parallel to the ground
y	airfoil ordinate
u,v	horizontal and vertical components of the velocity
V_o	free-stream velocity

The problem is linearized by assuming that $u(x,h) \ll V_o$ and hence disregarding u in comparison with V_o. As is shown by Malavard in Reference 207, this assumption is not valid very near the ground.

b. Channel Flow

For high-speed ground-effect machines with side jets, operating very close to the ground (channel flow GEM), it is assumed that the lift and pitching moment variation with changes in angle of attack can be represented by assuming one-dimensional channel flow underneath the vehicle and using Bernoulli and continuity equations, with an independent term accounting for the variation of the upper surface lift.

c. Mound Flow

It is assumed that, for a channel-flow GEM, the upper surface flow can be considered separately from the lower surface flow. Treating the upper surface like a mound or bump that the air particle must negotiate introduces the possibility of calculating an upper-surface lift coefficient. This lift coefficient is usually calculated approximately. It is found that quite large lift coefficients can theoretically be obtained from the upper-surface pressure distribution by proper shaping of this surface.

[281] Royce, W. W. and Rethorst, S. - A fundamental analysis is presented of the aerodynamics of a three-dimensional lifting surface translating in proximity to the ground. A mathematical model is formulated on the basis of a set of closed spanwise rectangular vortices representing the lifting surface and its side jets extending to the ground, and the corresponding image below the ground plane.

The finite mass flow through this channel underneath the machine permits a solution by matrix methods for the perturbation flow field generated by this vortex model, thereby providing the pressures, forces, moments, and power required by a GEM in forward flight.

A closed form solution is obtained for the limiting case where the surface approaches the ground. The principal value of a vortex singularity in this limit is obtained, and it is shown that on the upper surface the perturbation velocity, and hence the lift, vanishes; while on the lower surface the vortex strength becomes precisely the perturbation velocity. Thus, in this limit, the flow is reduced to one-dimensional channel flow.

[284] Saunders - The effect of the ground on the aerodynamic characteristics of wings is shown with the aid of a linearized two-dimensional model, followed by a description of a lifting-surface theory for finite wings of arbitrary planform. The effects of ground height, aspect ratio, sweep, taper, and non-planar geometries are investigated. Experimental data are found to compare well with theory.

BLANK

Table 1

References Dealing With Theory

References:	1	5	20	23	37	41	44	46	48	49	54	55	63	83	89	107	127	129	130	131	136	152	166	175	197	198	199	216	218	220	239	240	242	249	250	261	262	263	270
Configuration, or Geometry:																																							
Two-Dimensional	X	X	X	X		X			X		X			X				X	X	X	X		X		X		X			X	X	X				X	X	X	
Three-Dimensional		X		X			X	X		X		X	X			X	X					X	X	X	X	X	X		X				X	X		X	X	X	X
Flat Plate				X	X	X				X				X						X	X	X			X		X					X				X	X	X	
Curved Plate or Thin Airfoil	X								X		X							X	X			X		X	X		X		X			X	X				X	X	
Airfoil			X		X		X	X	X	X		X					X				X				X				X	X		X		X			X		
Unswept Wing							X										X								X														
Swept or Delta Wing								X																															
Method of Approach:																																							
Potential Flow	X	X		X	X	X		X	X			X	X	X	X		X	X	X	X	X	X		X	X					X	X	X	X			X	X		X
Conformal Transformation					X									X				X	X		X	X			X						X	X					X	X	
Lifting Line	X		X	X				X		X		X				X	X									X	X		X							X		X	
Lifting Surface																											X												
Method of Singularities	X		X	X		X	X	X	X		X	X					X							X	X					X				X		X	X		X
Electric Analogy										X	X		X																X	X									
Image Method	X		X	X	X				X		X	X					X							X	X		X			X		X	X	X			X		X
Approximate	X		X	X			X	X	X		X	X	X											X	X		X									X			X
Exact					X	X						X		X				X	X		X	X					X			X	X	X					X		
Phenomenological																	X											X					X	X	X				

Table 1 (Concluded)

References:	271	284	285	287	289	296	309	311	312	316	317	319	322	323	324	325	326	327	329	330	331	333	345	351	356
Configuration, or Geometry:																									
Two-Dimensional		X	X	X				X			X	X	X	X	X	X	X	X	X	X	X		X		X
Three-Dimensional		X			X	X	X		X	X												X		X	
Flat Plate				X									X	X	X	X	X	X	X	X					X
Curved Plate or Thin Airfoil											X										X				
Airfoil		X			X	X		X		X	X	X											X	X	
Unswept Wing		X				X																		X	
Swept or Delta Wing		X										X													
Method of Approach:																									
Potential Flow	X			X		X					X		X	X	X	X	X	X	X	X	X			X	X
Conformal Transformation				X							X		X	X	X	X	X	X	X	X	X	X	X		X
Lifting Line						X						X												X	
Lifting Surface		X			X																				
Method of Singularities		X				X		X		X														X	
Electric Analogy					X																				
Image Method		X			X	X		X															X	X	
Approximate		X			X			X			X												X		X
Exact				X									X	X	X	X	X	X	X	X	X				
Phenomenological										X															

Table 2

References Dealing With Experimental Methods of Approach

References:	3	5	6	7	8	9	11	13	14	15	17	18	20	21	22	26	27	28	29	31	35	38	39	44	46	51	52	53	58	59	60	65	67	68	69	70	72	73	74
Model	X		X			X	X	X	X			X	X	X	X		X			X					X	X	X	X	X	X	X	X	X	X	X	X		X	X
Full Size					X		X			X	X							X	X		X	X										X		X	X	X			
Two Dimensional													X		X																								
Three Dimensional	X			X		X	X	X	X			X		X		X				X					X		X	X			X								
Wind Tunnel	X		X	X			X	X	X			X	X	X	X					X					X		X	X	X									X	X
Towing Carriage						X	X		X								X												X		X								
Towed or Tethered																										X			X	X		X		X					
Flight Test or Free Flight							X		X	X	X							X	X		X	X										X	X	X	X				
Full or Partial Ground Board	X	X	X				X	X				X	X	X	X	X				X			X		X		X	X									X	X	X
Moving Belt Surface																																							
Image Method																																						X	
Over Ground Surface																		X			X																		
Over Water or Waves						X	X		X	X	X						X									X			X	X	X	X		X	X	X			
Test Technique		X												X									X																
Test Correction																								X															
Flow Pattern Study or Spray	X					X											X														X								

Table 2 (Continued)

References:	75	76	77	80	81	83	84	85	86	87	91	93	94	95	99	100	105	109	110	112	113	115	118	121	126	125	128	132	137	138	139	140	142	143	145	144	151	153	154
Model			X	X	X	X	X	X	X				X	X			X	X			X	X	X	X		X		X	X	X		X						X	X
Full Size	X						X				X				X				X	X					X		X		X		X								
Two Dimensional						X				X		X	X																										X
Three Dimensional			X	X	X			X						X			X				X	X	X	X		X		X											
Wind Tunnel	X					X	X	X	X			X	X	X			X				X	X		X		X		X		X		X						X	X
Towing Carriage		X		X	X																X		X																
Towed or Tethered		X		X	X				X									X											X										
Flight Test or Free Flight			X				X				X				X				X				X				X		X										
Full or Partial Ground Board			X			X	X	X	X			X	X				X				X			X		X		X		X								X	X
Moving Belt Surface																																							
Image Method							X		X													X								X									
Over Ground Surface							X																X						X										
Over Water or Waves	X	X		X											X	X		X	X	X			X		X				X		X								
Test Technique																														X		X	X	X	X	X			
Test Correction																																							
Flow Pattern Study or Spray						X	X	X																													X	X	

Table 2 (Continued)

References:	157	160	161	163	164	167	168	169	171	174	176	177	178	180	181	182	185	186	187	192	193	194	197	200	203	204	205	206	207	210	211	212	213	214	216	226	230	231	234
Model											X				X		X	X	X				X	X							X		X	X	X		X	X	X
Full Size	X	X		X			X	X	X	X				X								X			X	X	X	X		X		X				X			X
Two Dimensional																																							
Three Dimensional			X			X									X		X	X	X					X							X		X	X	X	X	X	X	X
Wind Tunnel			X								X				X	X		X	X				X						X		X			X	X		X	X	
Towing Carriage					X																		X																X
Towed or Tethered																	X							X									X						
Flight Test or Free Flight	X	X					X	X	X	X							X					X	X		X	X	X		X			X							X
Full or Partial Ground Board			X								X				X			X	X					X						X	X			X	X	X	X	X	
Moving Belt Surface					X																																		
Image Method																																							X
Over Ground Surface						X	X	X									X			X	X																		
Over Water or Waves	X								X	X		X	X						X		X	X			X	X	X	X	X	X		X	X			X			X
Test Technique			X																					X									X						
Test Correction																																							
Flow Pattern Study or Spray			X										X										X																

Table 2 (Continued)

References:	235	236	237	238	243	246	248	249	250	251	258	263	264	265	266	267	268	271	273	274	275	276	277	278	279	280	281	282	283	285	290	292	294	295	296	297	298	303	304
Model	X		X	X			X	X	X			X	X	X		X			X	X	X	X				X						X	X	X		X	X		X
Full Size		X				X		X															X	X	X	X	X	X	X	X									
Two Dimensional												X	X																										
Three Dimensional	X		X	X					X			X	X	X		X			X	X	X	X										X	X	X	X	X	X		
Wind Tunnel			X				X	X	X			X	X	X		X			X	X	X	X											X	X	X	X	X		X
Towing Carriage	X			X																																			
Towed or Tethered																																							
Flight Test or Free Flight						X		X															X						X	X									
Full or Partial Ground Board			X				X		X		X	X	X	X	X	X			X	X	X	X												X		X			X
Moving Belt Surface							X																																
Image Method					X		X				X				X			X																	X		X		
Over Ground Surface								X															X	X	X					X									
Over Water or Waves	X	X		X	X	X					X													X			X	X	X										
Test Technique										X							X														X					X		X	X
Test Correction																																							
Flow Pattern Study or Spray							X					X			X								X																

Table 2 (Concluded)

References:	305	306	307	312	316	317	333	334	336	337		339	340	341	342	348	349	350	351	353	354	355	356	357	360	361	362	363
Model	X	X	X	X	X	X	X	X	X	X		X	X	X				X	X		X			X	X		X	
Full Size		X					X								X		X			X				X				X
Two Dimensional													X													X		
Three Dimensional	X	X	X	X	X	X	X	X	X	X				X				X	X						X		X	
Wind Tunnel	X		X		X	X		X	X	X		X		X				X	X		X				X		X	
Towing Carriage			X	X			X			X													X					
Towed or Tethered				X													X											
Flight Test or Free Flight	X	X					X								X		X			X				X				X
Full or Partial Ground Board	X	X	X				X	X	X	X		X	X	X		X			X						X		X	
Moving Belt Surface																					X							
Image Method												X	X			X		X					X					
Over Ground Surface					X	X																	X	X				X
Over Water or Waves																				X				X				
Test Technique										X		X				X					X							
Test Correction												X																
Flow Pattern Study or Spray		X												X		X						X						X

Table 3

Reference [illegible] With Experimental Results

References:	3	5	6	7	10	11	13	14	15	18	26	[illegible]	[illegible]	30	31	35	46	49	50	51	52	53	54	58	60	61	62	63	64	69	70	72	73	74	76	77	80	81	83
Geometry Varied:																																							
Planform (tapered, swept)							X	X																	X														
Aspect Ratio							X	X																															
Thickness							X	X											X					X															
Tip Plate						X																		X				X											X
Tip Faired or Shaped						X																																	
Parameters Varied:																																							
Height			X			X							X	X		X		X			X	X		X	X	X		X			X							X	
Angle of Attack or Trim			X			X	X	X		X	X		X		X		X	X			X	X		X	X						X		X	X		X			X
Roll						X						X									X	X									X				X				
Yaw (Sideslip)				X		X						X																								X	X		
Flap Angle	X			X					X				X	X			X	X		X									X			X			X			X	
Quantities Measured:																																							
Lift	X		X			X	X	X		X	X	X	X	X	X	X	X	X			X	X		X	X	X	X					X	X	X		X			X
Drag or Resistance	X		X		X	X	X	X		X	X	X	X		X	X	X				X	X		X	X	X	X			X	X		X	X					X
Moment	X			X		X	X	X		X	X	X			X		X	X			X			X							X		X	X					X
Downwash		X																					X																

Table 3 (Continued)

References:	84	85	87	92	93	94	95	105	107	109	110	113	115	118	121	125	128	131	132	140	145	153	154	157	162	163	166	168	176	180	181	185	186	187	192	194	197	198	203
Geometry Varied:																																							
Planform (tapered, swept)												X				X																							
Aspect Ratio																X					X										X								
Thickness								X				X	X			X																							
Tip Plate								X					X																								X		
Tip Faired or Shaped												X	X																										
Parameters Varied:																																							
Height	X	X	X	X		X		X				X	X	X			X		X						X		X		X			X	X		X		X		
Angle of Attack or Trim	X	X					X	X				X	X	X	X	X								X							X	X					X		
Roll							X							X																	X	X		X					
Yaw (Sideslip)							X							X																									
Flap Angle		X								X		X														X		X	X	X									
Quantities Measured:																																							
Lift	X	X	X	X	X	X	X	X			X	X	X	X	X	X		X	X			X		X	X		X	X	X		X					X	X		X
Drag or Resistance		X		X			X	X			X	X	X	X	X	X		X	X									X			X					X	X		X
Moment		X			X	X	X	X				X	X	X	X	X	X	X	X				X								X	X	X				X		
Downwash									X											X			X						X									X	

Table 3 (Continued)

References:	211	214	216	224	225	230	231	234	235	237	238	243	246	248	249	250	257	263	264	265	266	267	271	272	273	274	275	280	285	288	292	294	295	296	297	298	300	302	303
Geometry Varied:																																							
Planform (tapered, swept)	X																			X																			
Aspect Ratio	X																			X																			
Thickness	X																																						
Tip Plate	X	X																X						X															
Tip Faired or Shaped	X																																						
Parameters Varied:																																							
Height	X	X				X	X							X				X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		X	X	X	X
Angle of Attack or Trim	X		X		X	X							X			X		X					X	X	X	X	X		X		X		X	X	X	X		X	
Roll	X																																						
Yaw (Sideslip)	X																																						
Flap Angle	X		X							X					X	X										X	X				X		X	X		X			
Quantities Measured:																																							
Lift	X	X	X		X	X	X				X		X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X
Drag or Resistance	X	X	X	X	X	X	X	X	X		X	X				X		X			X	X		X	X	X	X		X	X				X	X	X	X		
Moment	X		X			X					X					X	X	X				X			X	X	X		X		X		X	X	X	X			
Downwash															X																	X							

Table 3 (Concluded)

References:	305	307	309	312	316	317	333	334	335	337	339	340	341	342	349	350	355	356	359	360	361	362
Geometry Varied:																						
Planform (tapered, swept)		X				X																
Aspect Ratio		X																	X			
Thickness		X				X																
Tip Plate				X												X						
Tip Faired or Shaped																						
Parameters Varied:																						
Height			X		X	X		X		X	X	X	X	X	X	X	X		X	X	X	
Angle of Attack or Trim		X			X	X	X	X	X		X	X	X		X		X			X		X
Roll		X																				
Yaw (Sideslip)																						
Flap Angle					X				X			X			X	X		X		X		
Quantities Measured:																						
Lift	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X
Drag or Resistance	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X				X		X
Moment		X			X	X	X	X	X			X			X	X				X		X
Downwash			X	X									X				X					

Table 4

References Dealing With Applications

References:	2	3	4	6	7	8	9	11	12	13	14	15	17	21	24	25	26	27	28	29	35	38	42	43	45	46	50	51	52	56	57	59	60	61	64	65	68	69	70
Boat With Wing Between Hulls								X	X				X		X	X						X			X														
(Catamaran)																																							
Boat With Wings Outboard of Hull	X					X						X																								X			X
Integrated Planing Hull or Float						X																									X								
Wing																																							
Auxiliary Hydrofoil or Fin																																X				X			
Sponsons or Stub Wings							X											X									X	X					X			X		X	X
Jet Flap				X																									X										
Side Air Curtain Sealing									X								X																		X				
GETOL																																							
Landplane		X								X											X					X			X										
Seaplane or Amphibian					X	X								X													X				X		X			X			
Land Wheeled Vehicle																																							
Air Propulsion						X					X								X	X															X		X		
Water Propulsion								X				X	X																										
Landing or Taking Off		X																															X	X		X		X	X
Performance of Complete System								X			X		X							X	X						X			X						X			
Flying Fish			X																				X	X															
Seabirds Near Water Surface																																							
Natural Observation			X																				X	X															
Performance (Natural Phenomena)			X																					X															
Measurement (Natural Phenomena)																																							
Katzmayer, Betz-Knoller, or																																							
Lilienthal Effect																																							

Table 4 (Continued)

References:	71	72	74	75	76	78	79	80	81	83	85	86	87	88	90	91	93	94	95	97	98	99	100	101	102	103	104	105	106	108	109	110	112	113	114	116	117	118	
Boat With Wing Between Hulls																									X														
(Catamaran)																																							
Boat With Wings Outboard of Hull				X		X																X		X	X								X	X					
Integrated Planing Hull or Float				X				X	X													X		X															
Wing																																							
Auxiliary Hydrofoil or Fin																																	X						
Sponsons or Stub Wings					X			X	X											X	X	X									X								
Jet Flap											X	X	X	X			X	X										X	X	X								X	
Side Air Curtain Sealing											X	X																X	X									X	
GETOL											X				X														X	X									
Landplane										X																													
Seaplane or Amphibian			X	X	X			X	X										X	X	X	X	X	X	X						X	X						X	
Land Wheeled Vehicle																																							
Air Propulsion				X												X						X						X	X				X	X					
Water Propulsion																																							
Landing or Taking Off				X			X	X		X					X							X																	
Performance of Complete System		X		X																		X											X	X				X	
Flying Fish																										X	X									X	X		
Seabirds Near Water Surface	X																										X												
Natural Observation	X																										X										X		
Performance (Natural Phenomena)																										X									X				
Measurement (Natural Phenomena)																										X													
Katzmayer, Betz-Knoller, or																																X			X	X			
Lilienthal Effect																																							

Table 4 (Continued)

References:	122	123	124	125	128	131	134	135	139	145	147	148	149	150	153	154	155	157	159	160	161	162	163	164	165	166	167	168	173	177	178	179	180	181	183	184	185	187	
Boat With Wing Between Hulls	X	X																												X	X				X				
(Catamaran)																																							
Boat With Wings Outboard of Hull			X																										X				X						
Integrated Planing Hull or Float									X	X										X			X										X						
Wing																																							
Auxiliary Hydrofoil or Fin																																							
Sponsons or Stub Wings					X																																		
Jet Flap															X	X	X				X					X								X					
Side Air Curtain Sealing																																		X					
GETOL				X																	X	X															X		
Landplane				X	X				X																X														
Seaplane or Amphibian									X									X					X		X				X				X					X	
Land Wheeled Vehicle																																							
Air Propulsion			X						X											X								X					X						
Water Propulsion			X																												X								
Landing or Taking Off					X										X			X						X															
Performance of Complete System				X														X									X							X					
Flying Fish							X	X			X	X	X	X					X																				
Seabirds Near Water Surface							X												X													X							
Natural Observation							X	X			X	X	X	X																									
Performance (Natural Phenomena)							X																																
Measurement (Natural Phenomena)							X					X																											
Katzmayer, Betz-Knoller, or						X																														X			
Lilienthal Effect																																							

Table 6 (Continued)

References:	188	189	191	192	193	194	195	196	200	201	203	204	205	206	207	210	216	217	222	223	224	225	226	227	228	229	230	233	234	235	236	237	238	244	245	246	247	248	249
Boat With Wing Between Hulls											X			X		X									X			X							X				
(Catamaran)																																							
Boat With Wings Outboard of Hull	X										X	X	X	X		X									X						X								
Integrated Planing Hull or Float											X			X		X	X		X																		X		
Wing																																							
Auxiliary Hydrofoil or Fin																																							
Sponsons or Stub Wings											X													X					X	X									
Jet Flap				X																							X												
Side Air Curtain Sealing																																							
GETOL									X																														
Landplane																	X																					X	
Seaplane or Amphibian						X					X					X			X				X	X	X	X			X			X				X	X		
Land Wheeled Vehicle																										X													
Air Propulsion									X		X			X		X			X				X			X			X				X				X		X
Water Propulsion											X	X	X																		X								
Landing or Taking Off																X				X									X	X						X			X
Performance of Complete System											X	X	X	X	X	X					X	X														X			
Flying Fish		X					X	X		X																								X					
Seabirds Near Water Surface																		X																					
Natural Observation		X					X	X										X																X					
Performance (Natural Phenomena)			X					X										X																X					
Measurement (Natural Phenomena)																		X																					
Katzmayer, Betz-Knoller, or			X		X	X												X																					
Lilienthal Effect																																							

Table 4 (Continued)

References:	250	253	254	257	264	265	266	267	269	271	272	273	275	276	277	278	279	281	282	283	285	286	292	293	294	295	300	301	304	305	306	307	309	313	314	318	320	321	333
Boat With Wing Between Hulls (Catamaran)				X					X									X	X	X		X		X										X	X			X	
Boat With Wings Outboard of Hull																						X					X											X	
Integrated Planing Hull or Float Wing																																							
Auxiliary Hydrofoil or Fin																																							
Sponsons or Stub Wings		X																																					
Jet Flap			X			X	X	X		X															X							X							
Side Air Curtain Sealing					X														X	X													X						
GETOL					X	X	X	X			X			X																	X	X							
Landplane	X												X		X		X				X					X													
Seaplane or Amphibian		X																				X			X		X							X			X	X	
Land Wheeled Vehicle																													X										
Air Propulsion																		X	X	X		X																	
Water Propulsion																																			X				
Landing or Taking Off				X								X	X	X	X	X	X				X											X					X		X
Performance of Complete System														X		X		X	X	X	X									X	X								
Flying Fish																												X								X			
Seabirds Near Water Surface																																							
Natural Observation																												X											
Performance (Natural Phenomena)																							X					X											
Measurement (Natural Phenomena)																												X											
Katzmayer, Betz-Knoller, or Lilienthal Effect																																				X			

Table 4 (Concluded)

References:	336	337	341	342	344	345	346	347	348	349	354	355	356	357	358	360	361	362	363
Boat With Wing Between Hulls					X										X				
(Catamaran)																			
Boat With Wings Outboard of Hull				X			X												
Integrated Planing Hull or Float					X	X							X						
Wing																			
Auxiliary Hydrofoil or Fin							X												
Sponsons or Stub Wings													X						
Jet Flap		X	X			X			X		X	X					X		
Side Air Curtain Sealing						X					X								
GETOL						X					X								
Landplane	X													X		X			X
Seaplane or Amphibian					X														
Land Wheeled Vehicle																			
Air Propulsion					X	X													
Water Propulsion				X															
Landing or Taking Off										X			X			X			X
Performance of Complete System				X						X									
Flying Fish								X											
Seabirds Near Water Surface																		X	
Natural Observation																			
Performance (Natural Phenomena)																			
Measurement (Natural Phenomena)																			
Katzmayer, Betz-Knoller, or														X					
Lilienthal Effect																			

Table 5

Tabular Breakdown of Contents of References

References:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Illustrations			X	X			X	X		X	X		X	X	X	X	X	X			X					X		X	X									X	
Diagrams or Drawings	X	X	X	X	X		X			X	X	X	X	X		X	X	X	X	X	X		X	X	X	X			X		X	X		X	X	X	X	X	
Graphs or Charts	X		X	X	X		X			X	X		X	X		X	X	X		X	X	X	X			X					X	X			X		X		
Tables			X	X			X	X						X			X	X		X		X				X			X			X				X	X		
Formulas			X		X											X																					X		
Bibliography or Reference	X			X	X	X				X	X		X	X						X		X				X			X							X			
Patent Description		X										X							X					X	X														X
Proposal																																							
Final, Progress, or Summary											X																												
Report																																							
Textbook Discussion or Standard																																							
Work Source																																							
Thesis																																							
Comment of Unusual or Historical								X		X				X																X		X		X		X			
Interest																																							
Analysis of Previous Studies														X		X																		X	X				
Document not Generally							X		X																		X												
Available																																							
Not Searched						X																					X						X						

Table 5 (Continued)

References:	40	41	42	43	44	45	46	47	48	49	50	51	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
Illustrations			X				X										X	X	X					X		X	X		X	X	X				X		X		
Diagrams or Drawings		X		X	X	X	X		X	X			X	X			X		X	X	X	X	X	X				X	X		X		X	X				X	
Graphs or Charts		X		X	X		X			X							X		X	X		X						X	X		X	X	X	X		X		X	
Tables		X			X		X												X		X							X	X			X		X					
Formulas							X		X	X			X	X	X				X			X											X						
Bibliography or Reference		X			X		X			X							X				X	X							X		X		X						
Patent Description						X										X							X																
Proposal																											X							X					
Final, Progress, or Summary Report															X																					X			
Textbook Discussion or Standard Work Source																				X																		X	
Thesis																																							
Comment of Unusual or Historical Interest																		X		X	X					X		X		X				X			X	X	
Analysis of Previous Studies															X																								
Document not Generally Available								X																	X		X				X					X			X
Not Searched	X		X					X			X	X													X										X				

Table 5 (Continued)

References:	81	82	83	84	85	86	87	88	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	148	[illegible]
Illustrations			X		X	X				X				X				X	X					X			X							X		X		X	
Diagrams or Drawings			X		X			X	X				X	X	X	X	X	X		X	X	X		X	X	X			X		X	X	X	X			X	X	X
Graphs or Charts			X		X		X		X		X	X	X	X	X									X		X	X			X	X	X	X	X				X	
Tables			X		X	X																										X					X		
Formulas					X						X																					X	X						
Bibliography or Reference			X		X	X								X	X									X			X				X			X	X			X	
Patent Description																X	X			X	X				X														X
Proposal																															X	X					X		
Final, Progress, or Summary Report																																							
Textbook Discussion or Standard Work Source																														X									
Thesis			X																																				
Comment of Unusual or Historical Interest				X				X	X	X								X	X			X	X			X	X		X							X			
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References:	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162
Illustrations		X	X							X			X		X	X		X								X			X		X			X			X	X	X	X
Diagrams or Drawings	X		X		X	X	X	X	X	X		X			X	X	X	X	X	X	X	X	X	X			X			X	X						X		X	
Graphs or Charts			X		X	X	X		X	X						X		X					X				X			X	X	X			X					X
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References:	163	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202
Illustrations	X			X	X		X	X	X		X		X	X	X		X	X	X			X	X	X		X						X	X	X			X	X	
Diagrams or Drawings	X			X	X	X				X		X	X			X		X		X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X		
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Illustrations	X	X	X	X				X	X	X	X	X			X					X														X	X	X			
Diagrams or Drawings	X		X	X	X			X	X			X		X	X	X		X	X			X	X	X	X	X	X		X		X	X	X		X	X	X	X	
Graphs or Charts	X			X				X	X			X	X	X	X	X		X				X	X					X	X			X	X		X	X			
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Illustrations			X		X		X				X						X					X	X		X		X	X					X		X	X			
Diagrams or Drawings	X		X	X		X	X		X	X	X				X		X			X	X	X	X	X	X	X			X			X	X	X	X				
Graphs or Charts		X			X		X	X	X						X	X				X	X	X	X	X	X	X					X	X	X	X	X	X	X	X	X
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Illustrations	X	X	X		X							X		X	X		X							X	X	X	X		X	X		X		X		X		X	
Diagrams or Drawings	X	X	X		X	X	X		X	X		X	X	X	X	X	X		X	X	X		X	X	X	X	X			X	X	X	X			X	X		X
Graphs or Charts	X	X	X	X	X		X		X	X		X		X		X	X	X	X		X	X			X	X	X		X	X	X	X				X	X		X
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Illustrations														X		X	X				X	X					X	X	X	X			X	X									X		
Diagrams or Drawings		X	X	X	X	X	X	X	X	X	X	X	X	X		X	X			X	X	X		X	X	X		X	X	X	X	X		X	X			X	X	X	X	X	X		
Graphs or Charts			X	X	X	X	X	X	X	X	X	X	X	X		X	X		X		X	X							X	X	X	X		X	X	X	X		X	X	X	X	X		
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LITERATURE SEARCH AND COMPREHENSIVE BIBLIOGRAPHY OF WINGS IN GROUND EFFECT AND RELATED PHENOMENA

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(Last name, first name, initial)*

Foshag, William F.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1966	110	365

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A comprehensive survey and literature search is made of the general field of wings operating in ground effect and related phenomena. Comments are included of some of the papers published, to present a sketch of the methods of approach of a number of authors. The bibliography presents sources which consider the problem from the theoretical, experimental, and/or applications point of view. Tables are included which provide a convenient breakdown of the various sources, for a quicker method of locating specific references dealing with an area of special interest to the reader.

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Air Cushion Vehicle						
Seaplanes						
V/STOL Aircraft						
Hydrofoil						
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Bibliography: p.8-51.

Appendix B (p.53-77): Survey of theoretical papers.

Analytical subject tables: p.79-104.

A comprehensive survey and literature search is made of the general field of wings operating in ground effect and related phenomena. Comments are included of some of the papers published, to present a sketch of the methods of approach of a number of authors. The bibliography presents sources which consider the problem from the theoretical, experimental, and/or applications point of view. Tables are included which provide a convenient breakdown of the various sources for a quicker method of locating specific references dealing with an area of special interest to the reader.

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AIRPLANES, GETOL
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AIRPLANES, VTOL
FLOW, INTERFACE
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PLANING SURFACES
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Bibliography: p.8-51.

Appendix B (p.53-77): Survey of theoretical papers.

Analytical subject tables: p.79-104.

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